Forest Fire in the Fossil Record

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Abstract

Fire may not only be seen as a destructive force but also as a preservational mechanism. Charcoal, a fire residue, preserves anatomy allowing for the identification of plants, is inert, and may survive transport, burial and diagenesis. Evidence of fires in deep time, before man, comes predominantly from macroscopic charcoal deposits. Our earliest records of wildfire come from the late Silurian and early Devonian (420-400 million years ago) but evidence of fire through the Devonian (400-350 my) is rare, possibly because of low atmospheric oxygen. Atmospheric oxygen levels are thought to have risen rapidly through the Carboniferous and Permian (350-250 my) and this coincides with the spread of fire into a range of environments from lowland tropical mires to floodplains and in to upland regions. Sedimentological evidence suggests that post-fire erosion-depositional systems are more widespread in the fossil record than has been previously thought. Studies of charcoalified plants not only provide data on the evolution of plants but also of fire-prone vegetation. Fire has played an important role in Earth System processes for over 400 million years impacting on the atmosphere, climate and the evolution of terrestrial ecosystems. It is in this context that we should see the Earth as a ‘fire planet’ (S.J. Pyne).

Introduction

Fire has been called a 'global herbivore' (Bond and Keeley 2005) and it has been shown that fire has shaped global ecosystems for over 350 million years (Scott 2000, Bond and Keeley 2005). However, fire may also be considered as a major earth system process interacting with climate and the atmosphere as well as providing a possible driving force for the evolution and spread of new plants and biomes (Scott and Glasspool 2006, Berner et al. 2003, Osborne and Beerling 2006). In addition, as is obvious from other papers presented in this volume, post-fire erosion-deposition is a factor that has recently come to the fore yet it has not been widely recognized until now in the fossil record. A major problem is a lack of awareness of the phenomenom for many earth scientists but the recent paper by Shakesby and Doerr (2006) may help address this.

The main source of data on the fossil record of fires comes from charcoal, although the presence of soot and polyaromatic hydrocarbons (PAH) have also been used (Scott 1989, 2000, 2001, 2002; Jones et al., 1997; Wolbach et al. 1990, Finklestein et al. 2005). In studies of more recent fires, fire scars on trees have also been widely used (Westerling et al. 2006).

Wildfires produce a number of carbonaceous residues, which have a broad range of terminology (Jones et al., 1997). These include combustion products such as smoke, gases and soot as well as residues such as ash and charcoal (Fig.1). The range of methods for detecting such products and the confusion in their definition, has hindered rather than helped a broader discussion of the history of wildfire (see Jones et al. 1997, Forbes et al. 2006, Scott and Glasspool 2007).

In this chapter, I shall set out the ways in which combustion products are formed, recognized and used before providing a brief account of the geological history of wildfire and its significance in the earth system.

The recognition of fire in the fossil record

Wildfires may produce both solid residues or gases (Novakov et al. 1997). Both solid residues and gases may combine together to form smoke which may cause significant environmental damage, in particular to human health as well as causing the build-up of greenhouse gases which may affect climate (Pyne et al. 1996, Page et al. 2002, Flannigan et al. 2000). Most geologists are concerned with the solid particulate residues from wildfire, which is predominantly charcoal (Scott 2000, also known in the fossil record as fusain (Scott 1989)). However, the wide use of terms such as elemental carbon, black carbon etc. and the overlap in their recognition and definition has created some confusion (Forbes et al. 2006, Bird 1997, Schmidt and Noack 2000). Some of the residues in smoke include soot, which is formed by

the agglomeration of condensed hydrocarbons and tars (Jones et al. 1997). However, soot may not only form as a result of biomass burning but also for coal and oil so that presence in the fossil record cannot be used to signal exclusively the occurrence of vegetation fires (Belcher et al. 2005).

The largest of the combustion residues comprise charcoal - that is charcoalified and partially charred plants, all of which have the potential of being incorporated into the fossil record (Scott 2003). In the fossil record such material has been described under the term fusain and has been identified by coal petrologists under the group of macerals known as inertinites (Scott 2002, Scott and Glasspool 2007).

Charcoal may be recognized in hand specimen as being black with a silky sheen and showing anatomical structure under the hand lens, as well as having a black streak. Charcoals have also been characterized using a range of chemical and physical methods.

Charcoal

Chemical Changes

Charcoals have been characterized chemically using a range of techniques. Most woods, for example comprise around 70% cellulose and 30% lignin but during the charcoalification process these products break down with the cellulose being less stable than the lignin. It has been well established that the increase in temperature is the main driving force of chemical change, which causes the breaking of particular chemical bonds and changes in functional group chemistry (Bustin and Guo 1999).

When wood is heated rapidly by an ignition source such as lightning, volatile gases are produced which mix with atmospheric oxygen resulting in combustion. This combustion, then provides the heat for pyrolysis to occur which provides more flammable gases and leaves a charcoal residue. With sufficient time and oxygen supply, all the wood will be combusted but this is often not the case and the pyrolysis residue, or charcoal, remains. The initial temperature rise drives off moisture (up to 110˚C) before cellulose decomposition is initiated between 110-270˚C. At this stage both gases and tars may be produced. This breakdown continues up to 400˚C when lignin also breaks down and the formation of charcoal is completed around 500˚C when little tar or volatiles are driven off (Pyne et al. 1996).

The transformation of wood to charcoal has been studied using a range of techniques including electron spin resonance (Cope 1980), infra-red spectroscopy (Guo and Bustin 1998) and 13C nuclear magnetic resonance (Jones 1993). All these methods show the change in chemical structure with increasing temperature. It has also been shown that in general, plants retain their stable carbon isotopic signature through the charring process, although some exceptions have been reported (Jones 1994, McParland et al. 2007).

Physical Changes

Charcoal is characterized by exceptional anatomical preservation (Scott 2001) (Fig. 3) and together with the fact that it is relatively inert, means that it has a rich information content that is only now being widely exploited. Whilst charcoal may appear as small poorly preserved black fragments (Fig.2), study even under a hand lens will reveal anatomical as well as morphological preservation. The use of scanning electron microscopy reveals this anatomical preservation to its full potential (Scott 2001) (Figs. 3 and 5). The anatomical data may allow the identification of the plants as well as characters such as stomata on leaves (Fig. 5b,d) and growth rings in woods, which can be used as palaeoatmospheric and palaeoclimate proxies. Many new groups of plants have been identified from fossil charcoal deposits (Scott 2000). Even such delicate structures as flowers (Fig. 3d) and glandular hairs on ovules (Fig. 5g) may be preserved.

Whilst there may be some shrinkage during the charcoalification process (Prior and Alvin 1983, Lupia 1995) anatomical data survives. Cell wells, however may typically be homogenized between 300-325˚C.

When studied in polished blocks under oil in reflected light charcoal shows characteristic high reflectance (Figs.3e). Experiments have demonstrated that there is an increase in reflectance with temperature (Jones et al. 1991, Scott and Jones 1991, Bustin and Guo 1998, Guo and Bustin 1999, Scott and Glasspool 2007, McParland et al. 2007) (Fig. 7b) and with time (Fig. 7a) (Bustin and Guo 1998, Guo and Bustin 1999, Scott and Glasspool 2005). Charcoal reflectance may be used, therefore, to provide an estimate of minimum fire temperatures, an area that has yet to be widely exploited (Scott and Jones 1994, McParland et al. 2007).

Soot

Soot is often defined as a black carbonaceous substance, which is produced during the imperfect combustion of plant material but also of coal and oil. However, as pointed out by Jones et al. (1997) it has been variously and widely used in the literature normally comprising material formed via a gas-phase condensation process. The mixing of terms such as soot and black/elemental carbon creates significant difficulty, especially as much black carbon has been thought to be fossil charcoal (Forbes et al. 2006). Jones et al. (1997) proposed that soot be defined as “particles emitted with smoke and formed via gas phase processes gas-to-particle conversion. Particle size ranging from sub-micrometer (mainly) up to less than 1μm”.

The recognition of soot in the fossil record has remained controversial. Wolbach et al. (1990) reported soot from the days of the Cretaceous-Tertiary boundary, which they identified both chemically and morphologically, having a characteristic “grape bunch” morphology. However, soot is particularly difficult to extract and identify and may be derived not only from vegetation fires but also the burning of

coal and oil deposits. Such material may not be the best, therefore, to identify biomass burning in the fossil record (Belcher et al. 2005).

Polyaromatic Hydrocarbons (PAH)

One group of chemicals that has been strongly linked to vegetation fires in the polyaromatic hydrocarbons (PAH) (Zepp and Macko 1997). Many of these chemicals with high molecular weights are resistant to degradation and hence may be found in the fossil record (Killops and Massoud 1992). It is also possible to infer a vegetation source from the range of PAHs in a sample, as many are strongly linked to the burning of certain plants (Simoneit 2002). In addition, it is possible to distinguish PAHs derived from biomass burning from those derived from fossil fuel combustion (Zepp and Macko 1997). Additional data on compound specific isotopes have also shown potential of identifying biomass source (Zepp and Macko 1997).

In the fossil record the occurrence of PAHs to infer fire history has not been widely needed but they may be particularly useful in the absence of charcoal to infer the presence of fires. However the combined use of charcoal analysis and chemistry is always advocated (Finklestein et al. 2005).

Fire Scars

When trees are burned by a fire they may be charred yet survive. Often this charring results in the presence of a fire scar. The occurrence of fire scars to interpret fire history is of main use in the historic past where growth ring studies can help date fire events (Agee 1990, Whitlock and Millspaugh 1995). Many recent fire records from North America have used a combination of charcoal occurrence in lakes and peats together with fire scar data to obtain data on fire frequency and climate which have helped in modelling the relationship between fire and climate (Westerling et al. 2006).

It is not possible to use fire scars in deep time to interpret fire history but rare examples have been reported from fossil woods (Dechamps 1984, Putz and Taylor 1996).

Macro- and Micro-charcoal

Origin

During fires there are many potential sources of charcoal and each may yield different information. One of the most obvious sources are small charcoal particles that are lofted in smoke by the wind (Komarek et al. 1973). For example, leaves and fine twigs may be combusted in crown fires and the small (often less than 1mm) charcoal fragments may be transported by the wind away from the fire (Clark 1988). It has been shown (Clark and Patterson 1997) that heavier particles are deposited from the air sooner than smaller particles. Particles <63 μm may be transported many kilometers away from the fire site. It is

these particles that have been predominantly used for fire frequency analysis and have been used as evidence of backgrounds fires (Clark and Patterson 1997). However, microscopic charcoals may also be produced from surface fires burning both shrubs, herbs as well as litter.

Most macroscopic charcoals (>1 mm often up to 1 cm) are not formed by burning of crowns of trees but from the burning of shrubs, herbs and dead trees and litter (Fig. 2). A prerequisite of the formation of large quantities of macroscopic charcoal is a sufficient build-up of litter. In this case surface fires will burn and char the litter (Fig. 2a). Only the smaller charcoal fragments, which may include small charcoalified twigs, leaves and flowers may be wind blown (Fig. 2g). Most of the macroscopic charcoal is transported first by overland flow (Figs. 8a, b) following rainstorms after the fire, then as suspended load sediment in rivers and finally by bed load transport after becoming water-logged.

Experiments have shown that larger charcoal fragments take longer to waterlog (Nichols et al. 2000) (Fig. 9d) and hence may be transported further. Charcoal may be transported into the ocean and be deposited in a range of marine environments. It is unlikely that all occurrences of larger charcoal fragments indicate local fires as has been claimed by some authors (Clark and Patterson 1997).

A third source of charcoal is from the burning of peat (Cohen 1974). However, there have been few instances where this has been shown to be significant in the fossil record despite such material being petrographically characteristic (Peterson 1998).

Whilst botanical identification of microscopic charcoals <63 μm is not generally possible, it is often possible to identify the botanical origin of larger charcoals and hence their greater significance in fossil sediments.

Transport and Deposition of Charcoal

Charcoal may be transported by either wind or water or a combination of these and deposited in a wide range of environments from lakes and mires to rivers, estuaries and into the ocean. Charcoal may be transported during the initial phases of a fire mainly in smoke and by wind and post-fire by wind or water. There have been extensive studies, from both natural and experimental burns, that have tracked the movement of microscopic charcoal by wind (Clark and Patterson 1997) and these and other authors show that the particle size of windblown charcoal decreases away from the fire. It has also been shown (Clark et al. 1998, Lynch et al. 2004) that little macroscopic charcoal is moved by wind (Ohlson and Tryerud 2000). These observations have led to the view that the record of microscopic charcoal provides data on regional or background fires whereas macroscopic charcoal provides evidence of local fires (see Clark and Patterson 1997). However observational data from modern wildfires, from laboratory experiments and from the distribution of charcoal in ancient sediments suggests that this is not the case and that

macroscopic charcoals may be widely transported by water and deposited into most depositional settings (Nichols et al. 2000, Scott et al. 2000, Scott 2000).

Considerable amounts of macroscopic charcoals may be formed from surface fires charring plant litter and shrub or herbaceous vegetation (Fig. 2, also Scott et al. 2000). Some of this macroscopic charcoal may be selected and concentrated by wind after the fire has passed (e.g. charcoalified flowers concentrating in wind ripples, Fig. 2g, Scott et al. 2000) most is moved initially be water often in a slurry by overland flow (Fig. 8a, b). Large quantities of charcoal and sediment may be move in this way and eventually will flow into moving or standing water. In some cases, this initial movement will cause a sorting of the charcoal by size and organ (Scott et al. 2000b). Once in water charcoal will remain buoyant. Laboratory experiments have shown that smaller charcoal particles sink more quickly than larger particles which would allow larger particles to be transported further (Fig. 9). There is also a difference in the hydrodynamic properties of wood charcoals formed at different temperatures (Vaughn and Nichols 1998, Fig. 10) and of charcoals formed by different plant organs (Nichols et al. 2000) (Fig. 10). This work indicates that charcoal may be transported considerable distances in suspension and help explain their abundance in some near-shore marine sediments in the fossil record (Nichols and Jones 1992, Falcon-Lang 1998, Scott 2000).

Once waterlogged, charcoal may be transported as part of the bedload (Nichols et al. 2000) (Fig. 11). Despite being fragile, tumbler experiments have shown that the charcoal may be moved many 10's of kilometers without appreciable damage. However, to be incorporated into bedload sediments it has been shown by flume-tank experiments that only moderate currents will permit this to happen (Nichols et al.2000) (Fig. 11). Often, however, the charcoal may be transported into a lake, lagoon, onto a floodplain or into a mire and settle out of suspension.

Only by analyzing the botanical origin of a charcoal assemblage can an assessment be made as to what vegetation it has come from. Rather than microscopic charcoal being used to indicate regional fires and macroscopic charcoals to represent local fires, a mixture of microscopic and macroscopic charcoal indicates local fires, where as well sorted macroscopic charcoal assemblages may imply distance transport from the fire site (see Collinson et al. 2007).

Can We Recognize Post-fire Erosion in the Fossil Record?

A major feature of modern fire is that of post-fire erosion, as indicated by chapters in this volume (see also Moody and Martin 2001, Shakesby and Doerr 2006). However, the nature of the fossil record is that it records the history of sedimentation in depositional settings rather than in erosive upland settings. To identify the occurrence of post-fire erosion/deposition cycles we need evidence firstly of a fire, from the

occurrence of abundant charcoal and an unusual sediment in terms of thickness or grain size. This phenomenon has until now rarely been recognized in deep time. Indeed, fire as a whole, and its impact, has been rarely considered by sedimentologists working on ancient sediments.

However, a number of deposits may be identified as being related to post-fire erosion. In the Carboniferous, coastal sediments contain abundant charcoal with coarse angular sand grains, which suggest rapid deposition (Nichols and Jones 1992, Falcon-Lang 1998) and were almost certainly the result of post-fire erosion/deposition following major wildfires (Fig. 8a). Evidence is also found within Carboniferous and Permian peats (coals), where thick and sudden influxes of sediment and charcoal is common. This can be seen both in coals but also in premineralized peats. Finally a number of coarse sand deposits with charcoal from the Jurassic and Cretaceous may be formed in a similar manner (Scott 2000, Collinson et al. 2000, Jones 1997).

Post-fire erosion depositional systems in deep time may be recognized by: a sharp or erosionally-based sedimentary unit; a thicker than normal sediment-rich horizon; a coarser sediment; immature sediments; charcoal with a range of clast sizes (possibly with a range of organs) and commonly with non-charred plants in addition. However, it is only a combination of charcoal and sediment characteristics, that may indicate that a deposit is derived from post-fire erosion.

Quaternary and Pre-Quaternary Methodologies

There has been a significant dichotomy of methodologies for those studying the history of fire in the recent past and for those researching fire regimes in deep time. Most papers on Recent and Holocene fire histories use the microscopic charcoal record which may be linked to fire scar data, varve data or historical records (Bradbury 1996, Clark and Patterson 1997, Edwards and Whittington 2000). However, the questions being addressed for those interested in the deep time record may be different. In such cases it is the larger or macroscopic charcoal record that is used, as it provides evidence of the vegetation, which was burnt as well as data on fire temperature (Scott 2000, 2001).

The use of charcoal size categories

Fire may produce a wide range of charcoal particles from around 1 cm to less than 1 μm (Clark and Patterson 1997). Many smaller particles less than 125 μm are regularly wind blown although some may also be water transported (Fig. 1). Small particles may be prepared as part of palynological preparations and particles can be counted at the same time as pollen and spores. Microscopic charcoal counts through

lake or peat sequences have been used to interpret fire history (Campbell and Campbell 2000). Reworking of microscopic charcoals may cause some problems (Bradbury 1996, Edwards and Whittington 2000).

Some authors prefer chemical methods to identify charcoal concentrations (Winkler 1985) but to what extent all the charcoal is measured as opposed to high temperature charcoals alone may be debated (see Schmidt and Noack 2003, Forbes et al. 2006, Scott and Glasspool 2007).

Larger charcoal fragments have often been studied by those interested in fire in deep time. There are several reasons for this: the ability to recognize charcoal (Figs. 2, 4) (Scott 1989); the anatomical preservation hence allowing the identity of the plant to be ascertained (Figs. 3, 5) (Scott 2001) and the ability to derive reflectance data for fire temperature interpretations (Scott and Jones 1994, Scott and Glasspool 2005, McParland et al. 2007) (Fig. 7).

What Can We Learn From Fossil Charcoal?

The excellent preservation of charcoalified plants (Figs. 2,4) allows a wide range of morphological and anatomical data to be derived allowing not only organ and species identification but also information concerning growth and ecology to be gained (Scott 2001). However, plants may be exposed to a wide range of temperatures during charring and experiments have allowed relationships between physical and chemical characteristics caused by the charring process to be identified (Scott 1989, Cope 1980, 1981, Scott and Jones 1991, Jones et al. 1991, Jones 1993).

Experimental charcoalification experiments

In the fossil record, charcoal has been called fusain (Scott 1989). Some researchers doubted that fusain represented charcoal and was formed by fire and some researchers persist in that view (see Scott 1989, 2002, Scott and Glasspool 2007). Much effort has gone into demonstrating the similarities, both chemical and physical, between charcoal and fusain, and experimental charcoalification has played a major role in this discussion (see Cope 1980, 1981, Jones et al. 1991, Scott and Jones 1991, Bustin and Guo 1998, Guo and Bustin 1999, Scott 2000, Scott and Glasspool 2005, 2007, McParland et al. 2007).

Controlled charring experiments have shown that the reflectance of charcoal as seen in polished blocks under oil (measured at a wavelength of 546 nm) increases with increasing temperature (Fig. 7b). This gave rise to the idea that charcoal reflectance might be used to interpret fire temperature (Jones et al. 1991, Scott and Jones 1994). Additional studies (Guo and Bustin 1999, Bustin and Guo 1998, Scott and Glasspool 2005, 2007) have shown that time also played a role. However, it was also shown in these studies that reflectance stabilizes after a few hours (Fig. 7a) and thus if a piece of wood charcoal had a

reflectance of 2.0 R_o then it probably experienced temperatures over 400˚C (Fig. 7a). This provides the idea of a minimum temperature estimate of charcoal formation and provides some idea of likely fire temperatures (Fig. 7b). Reflectance data appears to correlate with known fire temperatures (Scott and Jones 1994, Scott et al. 2000).

New research on a variety of plant and other materials shows that this increase in reflectance with temperature is common. For example, in addition to wood, fern tissues and fungal material also show thus pattern (Scott and Glasspool 2007, McParland et al. 2007). The use of charcoal reflectance as a fire temperature proxy has yet to be fully exploited.

Charcoal and the Carbon Cycle

A significant problem is any consideration of charcoal and the carbon cycle comes from the diversity of combustion products and residues from vegetation fires (Jones et al. 1997, Bird 1997, Schmidt and Noak 2000, Forbes et al. 2006) and a general lack of agreed nomenclature and methods of study. These authors suggest a good starting point into the literature and only some brief comments will be provided.

In many marine sediments black/elemental carbon has been documented (Goldberg 1985, Smith et al. 1973) and this has also been found in more ancient deep water sediments (Herring 1985). However, some particles can be identified microscopically, as small charcoal fragments based upon characteristic morphology (Griffin and Goldberg 1979, Goldberg 1985), others may represent soot or other carbonaceous particles.

Analysis of the fossil record does show that large quantities of charcoal may be buried in a wide range of sediments including in peat mires and as it is relatively inert (not necessarily pure carbon) it survives and hence contributes to the carbon sink.

Extensive fires may generate considerable CO_2 from biomass burning but in the long term it is the conversion of wood to charcoal, which provides a mechanism for increased carbon burial. As will be discussed later, this has implications for both long-term atmospheric composition and climate change.

Soot, Carbon, PAH - How reliable as indicators of ancient forest fires?

If there is debate about modern fire combustion products and residues and their characterization, there is also uncertainty for some in identifying such materials in deep time. In many cases rocks need to be dissolved to release their organic materials and the separation of the different organic fractions with different origins may be problematic. Four main categories of combustion products and residues have been identified in sediments from deep time.

The most easily extractable and recognizable of the combustion products is charcoal, often called fusain in ancient sedimentary rocks. This is easily released by simple sieving (often using a 200 μm sieve

(Figs. 4b,e,f). However, occurrences in shales or siltstones/sandstones (Figs. 4a,c,d, 8c,d,e) involves the use of hydrofluoric acid (HF), limestones the use of diluted hydrochloric acid (HCl) and coals the use of nitric acid (HNO_3) (see Pearson and Scott 1999 for techniques of maceration). Many charcoal fragments are easily identifiable, some specimens may be only partially charred (Jones et al. 1993). The occurrence of macroscopic charcoal in ancient sediments is a reliable indicator of wildfire. Only with the analysis of the plant organ and identity is it possible to identify a forest fire, for example.

Charcoal is very brittle and may be easily crushed upon burial in sediment. Micro-charcoal is more problematic in that it may represent wind-blown fire charcoal from a contemporary fire, water borne charcoal and in some cases reworked charcoal. Micro-charcoal has been widely used in Quaternary studies (Patterson et al. 1987, Clark and Patterson 1997) but it may be more difficult to identify in some more ancient sediments (Highton et al. 1997). This is because organic material becomes coalified and blacker during burial diagenesis. Separating on a palynology slide black coaly particles from black charcoal particles may be very difficult, especially if they are small (<63 μm).

Soot is very difficult to extract from sediments and identify. It is different from charcoal in that it is a product formed by combustion and comprises of small carbon particles. When dissolving sediments to study the organic matter it is possible to generate organic precipitates which may be difficult to distinguish from soot (Belcher et al. 2005). Soot has been reported in some sediments (Wolbach et al. 1990), it has not been widely reported and it may, in addition, be derived from a number of sources- biomass burning as well as from natural coal and oil fires.

Polyaromatic hydrocarbons (PAH) have only recently been used to interpret fire signals (Killops and Massoud 1992, Finklestein et al. 2005) in the fossil record. It is not entirely clear if such compounds may migrate in sediments or could be formed by some diagenetic processes but some characteristic compounds may be useful as a fire signal in the absence of charcoal but its use is strengthened when combined with charcoal occurrence (Finklestein et al. 2005).

Fire and Climate

There is a strong link between fire and climate (Terasmae and Weeks 1979, Fosberg et al. 1993, Carcaillet et al. 2001) and this interest and relationship has been heightened with discussion concerning global warming (Page et al. 2002, Westerling et al. 2006). It is clear that climate is likely to be a major driver of fire, especially catastrophic fire. In areas where there have been few fires, fuel build-up may occur. If there are increased periods of drought then a fire may spread, burn very hot and prove catastrophic both to the vegetation but also may lead to major post-fire erosion (Robichaud and Elsenbeer 2001).

Unfortunately, since it is possible to interpret fire and climate on a decadal or even millennial scale, understanding the relationship on a million year timescale is much more difficult. In addition, there is the added complication of atmospheric oxygen changes that are likely to affect fire intensity and fire frequency. We might assume that fires would be less frequent during cooler and wetter periods in Earth history but there has been attempt to examine this on a tens of millions of years time scale. It is possible to note that climate may have an effect on fire systems at some intervals in Earth history. It has been observed that fires were common through the Paleocene (65-55 my). Charcoal beds are common, for example in southern England (Collinson et al. 2007). However at the Paleocene-Eocene boundary there was a period of rapid global warming which had a major effect upon terrestrial systems (Gingerich 2006). An examination of the distribution of Eocene charcoal indicates that fires were not common (Scott 2000). In the section in southern England, which crosses the Paleocene-Eocene boundary (55.8 my), charcoal becomes rare or absent after the onset of the Palaeocene-Eocene Thermal Maximum (PETM) and Collinson et al. (2007a, b) argue that this is caused by a significant change in rainfall.

A much more comprehensive documentation of charcoal records in deep time are needed before a full analysis of the long-term relationship between fire and climate can be addressed.

Fire and Atmosphere

The interaction between fire and the atmosphere is widely recognized. However, the importance of fire in affecting atmospheric composition over geological time has only recently been discussed (e.g. Lenton 2003, Berner et al. 2003).

Oxygen

While charcoal forms in the absence of oxygen, fire can only be sustained in its presence. It has been demonstrated that a fire cannot be sustained when there is less than 13% atmospheric oxygen (todays value is 21 % - PAL, the present atmospheric level) (Chaloner 1989, Cope and Chaloner 1980, 1981). Experiments have indicated that with increasing oxygen wetter plants may burn (Watson et al. 1978, Wildman et al. 2004) and an upper threshold of 35 % oxygen provides the basis of a ‘fire window’ (Jones and Chaloner 1991). A range of experiments suggests that below 13 % O_2 no fire would spread and there would be an absence of charcoal in the fossil record, between 13-16 % fires would be rare and only very dry plant material would burn. This would mean that only vegetation, which was liable to dry out, would burn. Between 18-23 % fire occurrences would be similar to those under the present atmospheric level of 21 % O_2. At >25 % O_2 fires would become more widespread and at >30 % fire would be frequent in all environments (Watson et al. 1978, Wildman et al. 2004, Scott and Glasspool 2006).

All major models of atmospheric oxygen show variation through Phanerozoic time, especially in the last 400 million years (Berner et al. 2003, Lenton 2003, Berner 2006). Most models agree with a period of high oxygen during the Carboniferous from 350-300 million years. Scott and Glasspool (2006) have shown that this rise in oxygen may be seen in the charcoal record where as oxygen rose fires became more widespread and common in all environments and even thick Permian coals may be composed of over 70 % charcoal.

Modelling suggests a fall in oxygen at the end of the Permian around 250 million years ago to below the PAL in the Triassic (Berner 2006). However, models that suggest very low oxygen levels in the Jurassic, below 13 %, are not in agreement with the charcoal record. The Cretaceous (120-65 my) is of particular importance. It is during this period that flowering plants evolved. Many flowers are found preserved as charcoal (Friis et al. 2006). Numerous models have indicated that oxygen levels were elevated above PAL during this period (Berner et al. 2003, Lenton 2003). However, a recent model (Berner 2006) suggests and oxygen level of <PAL. The abundance of charcoal through the Cretaceous is a wide range of environments (Scott 2000, Collinson et al. 2000, Scott and Stea 2002, Falcon-Lang et al. 2003) suggests a higher level. It is clear, however, that there are significant feedbacks between atmospheric oxygen and fire (Fig. 13)

Carbon dioxide

There is an interesting relationship between fire and atmospheric CO_2. It has been recently suggested that there is a direct link (Carcaillet et al. 2002) but systems analysis indicates a strong fire feedback and that CO_2 levels may be at least indirectly linked to fire (Lenton 2003, Berner et al. 2003). Berner et al. (2003) in their systems analysis (Fig. 13) show that with increasing oxygen there is increasing fire, which in turn causes a decrease in land biomass (the path b-c-j-g in Fig. 13). They suggest this leads to less organic matter burial, less oxygen production and thus is a negative feedback. They also point out that fire may also lead to a positive feedback with regard to atmospheric oxygen exemplified with the production of charcoal (Berner et al. 2003). As charcoal is inert and tends not to biodegrade its burial leads to organic matter preservation which in turn leads to increased oxygen production, a positive feedback represented in the path b-a-i-g (Fig. 13). In addition, increased burning may give rise to increased erosion and more transport of sediment and charcoal to the sea, which enhances organic matter burial and raises oxygen levels (path b-c-d-e-g, Fig. 13).

While burial of carbon may lead to a rise in oxygen it may also lead to a fall in carbon dioxide level. This is well illustrated by models of CO_2 through time, which shows in the late Paleozoic there is a rapid fall in CO_2 levels as O_2 levels rise. This fall in CO_2 provides the stimulus for the onset of the late Paleozoic ice age.

Fire In Different Ecological and Geographic Settings

In today's world, fire systems vary in relation to vegetation type, climate, latitude and geomorphic setting. However, fire is an integral part of many terrestrial ecosystems, from the northern coniferous forests to the equatorial mines and including grasslands and forests (Pyne et al. 1996, Agee 1990, Cohen 1974, Crutzen and Andrae 1990, Johnson 1984, Sandford et al. 1985, Stocks and Kauffman 1997).

In the fossil record, evidence of fire has been found in most sedimentary environments from temperate to tropical areas and from uplands to lowland mires (Scott 2000). Charcoal derived from upland fires have been reported from the Carboniferous (Scott 1974, Scott and Chaloner 1983, Falcon-Lang and Scott 2000) and from the Triassic/Jurassic (Harris1958). Charcoal occurs commonly in lowland fluvial sediments from bed-load sandstones or the Jurassic and Cretaceous (Cope 1993, Scott 2000, Collinson et al. 2000) to over-bank floodplain fires of the Carboniferous (Scott 1978) and Cretaceous (Scott and Stea 2002, Friis et al. 1985). Charcoal is particularly common in peat deposits (coals) and occur abundantly in all ages (Scott 2000), but are particularly abundant in the Carboniferous, Permian and Cretaceous (Scott and Glasspool 2006a, Scott and Stea 2002).

Charcoal also gets washed into both shallow and deep marine sediments. Extensive seashore marine charcoal beds have been reported for the Carboniferous (Nichols and Jones 1992, Falcon-Lang 1998) and have also been reported as a significant component of late Devonian marine black shales (Rimmer et al. 2004). There has been a significant reporting of charcoal deposits since the year 2000 when a volume of fire and the paleoenvironment was published (Scott et al. 2000a) and continued reporting of charcoal in deep time will allow the unravelling of ancient fire systems more completely than is currently now possible.

The Geological History of Fire

The first fires

The two basic criteria for the occurrence of fire in the fossil record is the evolution of a land vegetation and sufficient atmospheric oxygen for fire to be sustained and spread (Fig. 14). In addition, there also needs to be a build-up of fuel. Vascular plants first evolved on land probably in the Silurian (430 my) (Scott 2000b). These plants were relatively small being no more than 10 cm tall (Edwards and Wellman 2001). We have evidence of charcoalified plants from the latest Silurian (400 my) (Glasspool et al. 2004) but records are scarce. Charcoalified plants have also been reported from the earliest Devonian (Edwards and Axe 2004), so small wildfires must have occurred at that time.

While land plants continued to evolve and diversify and become larger (Kenrick and Crane 1997) through the Devonian, we have little evidence of fire from the fossil record of charcoal (the charcoal gap, Scott and Glasspool 2006). This may be because atmospheric oxygen levels fell at this time (Scott and Glasspool 2006).

Evolution of widespread fire systems

Trees first evolved during the middle of the Devonian Period (380 my) and by the end of the Devonian there were extensive coastal forests dominated by the tree *Archaeopteris/Callixlon* (Meyer-Bethaud et al. 1999). Despite this, we have little evidence of extensive forest fires. Modelled atmospheric oxygen is shown to increase in the late Devonian so that fires may be sustained (Berner 2006, Scott and Glasspool 2006) (Fig. 12).

We have only scattered records of charcoal in late Devonian terrestrial sediments and the vegetation being burnt appears to be dominated by fern-like shrubby plants rather than trees indicating the occurrence of surface fires. Microscopic charcoal from such fires may be transported by wind into the ocean. Petrographic studies of late Devonian black shales (Rimmer et al. 2004) have shown that there is a rapid rise in the concentration of charcoal in these sediments at the end of the Devonian which indicates a rise in the spread and frequency at this time (Rimmer et al. in review) and this may reflect rising atmospheric oxygen levels (Scott and Glasspool 2006).

By the Devonian/Carboniferous boundary extensive charcoal deposits are recognized and the sedimentary environments in which charcoal is found and the vegetation being burnt suggests the spread of fires into a wide range of environments through the Mississippian (350-320 my)(Scott and Glasspool 2006). Extensive charcoal beds are found throughout the Mississippian and evidence from the charred plants and sediments suggests (Fig. 8c) very widespread fires that had a significant impact on the environment (Nichols and Jones 1982, Falcon-Lang 1998, 2000, Scott 2000).

Diversification of fire systems

It has been suggested from atmospheric models that oxygen concentrations rose through the Carboniferous and Permian to significantly above the present atmospheric level of 21 to 30-35 % (Berner et al. 2003, Berner 2006) (Fig. 12) and at these levels fires may be maintained in much wetter vegetation (Wildman et al. 2004). Wetland peat-forming mires also evolved during the late Mississippian and at this time evidence of fires are found abundantly in coals. Charcoal, which represents the inertinite group of macerals (Scott and Glasspool 2007) is common throughout the Pennsylvanian and Permian (Scott and Glasspool 2006) in coal seems indicating frequent fires in wetland mire systems (Scott and Jones 1994).

A high level of atmospheric oxygen may have allowed wetter vegetation to burn (Scott and Glasspool 2006).

Evidence of fires in other lowland ecosystems is shown by the presence of charcoal in floodplain shales (Scott and Jones 1994). In addition, charcoal is often found in fluvial sandstones which have drained burnt upland vegetation (Falcon-Lang and Scott 2000) and we have evidence of charcoals from early Pennsylvanian cave deposits of fires through conifer and cordaite vegetation living in drier upland habitats (Figs. 5a, b, 8d).

While evidence of widespread fire is found throughout the late Palaeozoic (see Scott 2000, Scott and Glasspool 2006) there is much less evidence of widespread fire systems in the succeeding Triassic. It is possibly related to a major fall in atmospheric oxygen at this time (Berner 2006).

In the Mesozoic charcoal is abundant in a wide variety of sedimentary systems. Charcoal becomes frequent in the Middle Jurassic (Fig. 4a) and there is evidence of fires related to drier intervals (Cope 1993, Morgans et al. 1999). Charcoal is especially abundant in the Cretaceous (Fig. 8e) (Collinson et al. 2000, Scott 2000, Scott and Stea 2002). It is during this period that flowering plants (angiosperms) first evolved. Many of the early flowering plants were small herbaceous herbs and often their flowers are preserved as charcoal (Friis et al. 2006). It is possible that regular fires through angiosperm dominated vegetation aided in the diversification and success of this group of plants.

Fires were abundant throughout the Cretaceous and earliest Tertiary but claims of a global wildfire at the Cretaceous-Tertiary boundary (Woolbach et al. 1990) have not been supported from charcoal studies (Belcher et al. 2005).

A major innovation in vegetation biomes was the development of grasslands, in particular savannas dominated by C4 grasses. Bond and Keeley (2005) have suggested that it is fire that maintains this savanna. This would imply a long interaction between fire and grasslands. Further, Osborne and Beerling (2006) have suggested that fire was the stimulating force in the evolution of C4 grasslands.

There is no question of the importance of fire in shaping not only the biosphere but also the significance of fire feedbacks in the evolution of the Earth system as a whole. All of this happened before man appeared on the planet.

Impact of fire on the environment

The impact of fire upon the environment is well understood (Crutzen and Goldammer 1993, Rundel 1981, Cypert 1973). However, less is known in a fossil context and many issues that form the

basis for intense discussion concerning modern fire systems have not been addressed. In addition, time adds an extra important dimension.

Four areas that are of current concern are discussed for those studying ancient fire systems: impact on plant evolution; impact on fossil preservation; impact on plants; and post-fire erosion.

Impact of fire on plant evolution

While it may be accepted that fire may play a role in shaping plant communities - giving rise to fire-prone vegetation, there has been less consideration of how fire may have helped in plant evolution/diversification. Cause and effect is, however, very difficult to unravel in the fossil record, thus a few observations and suggestions may be made at this time, awaiting further study.

Many early ferns (late Devonian/Early Carboniferous) are often found as charcoal (Scott and Galtier 1985) and burnt ferns are frequently encountered in periods such as the Cretaceous (Harris 1981). This has led to idea of fern 'prairies' being maintained by fire (Collinson et al. 2000). However as ferns may survive fire and regenerate very quickly, it is possible that fire regimes of the early Carboniferous encouraged their spread and diversification.

Likewise, many early conifers are also preserved as charcoal (Scott 1974, Scott and Chaloner 1983, Scott 2000) and fire may have played a role in their diversification, as they were some of the first plants to have lived in drier uplands.

Most records of early angiosperm flowers in the Cretaceous come from charcoal deposits. Most of these appear to come from small herbaceous forms and fire may have maintained an open habitat in which they could thrive.

Fire has also been invoked as a mechanism to create the savannah biome and in the evolution of C4 grasses (Osborn and Beerling 2006,) but more research is needed to prove these hypotheses.

Impact of fire on fossil preservation

It is intuitive to believe that fire is a destructive force rather than a preservational mechanism. However, the rapid heating of pyrolysis caused by a fire, and conversion of plant tissues to charcoal, has the effect of preserving both the morphology and anatomy of the plants as well as converting cell walls to carbon-rich and non-biodegradable materials (Scott 2001). The charcoalification process may cause some shrinking of plant tissues (Prior and Alvin 1981, Lupia 1990) but the overall relative dimension of the plants and often not changed. Other effects include the homogenization of the cell walls with the loss of the middle lamella but this does not affect botanical anatomical data (Jones 1993).

Studies using scanning electron microscopy on charcoalified plants following recent fires, show that a wide range of plants and plant organs may be beautifully preserved such as wood, leaves, flowers and

seeds (Figs. 3,5). Flowers may show exquisite preservation (Fig. 3d) and despite being fragile may be both wind and water transported (Scott et al. 2000). Likewise in the fossil record a wide variety of charcoalified plant organs have been reported, not only flowers but even ovules with glandular hairs (Figs. 5e,f,g). Often charcoalified plants look fragmentary, black and uninteresting (Figs. 4c, d) but initial observations under a hand lens and subsequent microscopical studies using scanning electron microscopy reveal a wealth of important data that may be used to unravel plant history, ecology and evolution.

Impact of fire on plants

There are many vegetation types, for example in Australia and Africa that have evolved in response to fire. In some case plants will not reproduce without fire. This leads to the conclusion that fire must have played an important role in the evolution of some biomes. It has become well established that savannas are kept open by fire (Bond and Keeley 2006) and others have indicated that the evolution of C4 grasslands may have been a response to fire regimes (Osborne and Beerling 2006). It is possible that fire may have also played a role in the rise and spread of other plants and plant communities such as ferns and early angiosperms, as many of these are found as charcoal and are associated with frequent fires (Scott and Galtier 1985, Friis et al. 2006). As the significance of fire in Earth systems processes is more fully understood then the role of fire in stimulating plant evolution may be addressed more widely.

Burial and Preservation by post-fire erosion

Over the past 20 years the scale and significance of post-fire erosion and deposition has been more fully appreciated. As demonstrated by several authors in this volume, fire may not only destroy or alter surface litter but also affects the soil so that subsequent rainstorms may cause extensive erosion and sediment transport initially by surface flow (Figs. 8a, b). The mix of sediment and charcoal may be transported down hillslopes and even across floodplains before being deposited in rivers or lakes. The phenomenon of post-fire erosion is now considered a major sedimentological process (Cannon 2001, Cannon et al. 2001, Moody and Martin 2001, this volume). However, post-fire erosion has not been widely recognized in the Pre-Quaternary fossil record. It has been recognized that many alluvial fan sequences may be triggered as a result of post-fire erosion processes (Meyer et al. 1992).

Examination of the fossil record indicates that post-fire erosion and deposition is a more important phenomenon that has been previously realized. There are numerous examples where sudden influx of sediment with abundant charcoal is found, for example, in the early Carboniferous of Ireland, in the Triassic of New Mexico, in the Jurassic of Yorkshire, the Cretaceous of the Isle of Wight (Nichols and Jones 1991, Falcon-Lang 1998, Collinson et al 2000, Scott 2000, Zeigler 2003).

The rapid erosion and burial of sediments may also have had an effect on the global atmosphere. It is often not appreciated that many thick coals from the Permian of India or the Early Cretaceous of Canada are deposits with over 70% charcoal and probably were the result of post-fire erosion/depositional processes.

How can the past help us understand the present and future of wildfire?

While modern fire systems can help us understand ancient fires, the geological record can offer the perspective of time, where there have been changes in atmospheric composition, changes in climate including periods of rapid global warming. In each case it is possible to see effects that can only be modeled into the future.

The fossil record offers a glimpse of the rare event or a large event, so that, for example, the impact of a large fire had on estuarine fish communities in the Carboniferous may offer a new perspective to fire scientists studying only their fire area.

What the fossil record does show, however, is that major wildfires were an integral part of the Earth system for hundreds of millions of years before man and we may regard man as an additional complicating factor.

Our understanding of ancient fire systems is based mainly on studies of fossil charcoal. However, charcoals are rarely studied by those interested in modern fires. Perhaps some of the data and techniques used for the study of macroscopic charcoals may be of use in the current debates concerning the recognition and definition of fire intensity and burn severity?

Future Directions

Our understanding of ancient fire systems is relatively poor. The significance of fires in the Pre-Quaternary, before the advent of man, has only recently been appreciated. Likewise, the significance of charcoal as a major data source is still not fully appreciated. Charcoal studies may contribute to not only understanding past fire systems but may also help in the interpretation of both fire and post-fire processes. Several important questions need resolution:

- Can charcoal provide data on the question of fire intensity and burn severity?
- Are all charcoal assemblages representative of the vegetation being burnt?
- Can we use charcoal assemblages to recognize different vegetation types?
- Can we use charcoals to interpret fire type?
- Are most macroscopic charcoal assemblages derived from plant litter and surface plants?

- How might sedimentary processes bias charcoal assemblages?
- Can we use charcoal to identify sedimentary deposits formed by post-fire erosion/depositional processes?

In relation to our understanding of ancient fire systems many of the above questions are still relevant. We might add a time dimension:

- What is the role of fire in 'Earth systems processes'?
- How has the evolution of the atmosphere been affected by or have an influence on the diversification of fire systems?
- What is the role of charcoal in long-term carbon storage?
- How does fire influence plant evolution?
- How might some biomes be a direct result of fire activity?
- What are the major drivers of fire systems in deep time – oxygen levels, climate or both?

It is clear that we are only just scratching the surface of charcoal studies and the importance of ancient fire systems is only just being appreciated by the wider science community

Conclusions

Fire products and residues include gases, organic compounds such as polyaromatic hydrocarbons (PAH), soot and charcoal. Whilst soot and PAHs have been described from ancient sediments, it is the occurrence of charcoal that provides the best evidence of ancient forest fires.

Charcoal preserves plant anatomy and allows the identification of plant organ and species. Plants charred at increasing temperatures show increased cell wall reflectance when studied in polished blocks under oil. This data may help in the interpretation of fire type and fire temperatures as well as indicating fire intensity and burn severity.

Evidence of the first fires comes from the late Silurian/early Devonian but it is not until the Carboniferous that fires became diverse and widespread. This may be in part due to a rise in atmospheric oxygen concentration at this time. The suggestion of high oxygen concentrations in the Carboniferous and Permian (over 30 %) may be supported by the occurrence and abundance of charcoal in coals at this time.

Fires may have stimulated the evolution of a range of plants and may have helped in the evolutions and maintenance of the savanna biome.

Major fires from the Carboniferous onwards may have generated major sedimentary sequences as post-fire erosion.

Strong feedbacks between fire and the atmosphere have been identified and especially strong links have been suggested between the importance of fire with increasing oxygen and the link between rising oxygen and falling carbon dioxide levels and the erosion of rocks.

Fire has played an important role in the Earth system for at least 400 million years.

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Figure Legends

Figure 1. Transport of fire combustion products and residues. Particulates and gasses are transported by wind and most macroscopic charcoal is produced from the burning of surface vegetation and litter and is transported by water.

Figure 2. Modern charcoal assemblages: a) charred surface litter from the 2002 Hayman fire, Colorado, U.S.A.; b) detail of material collected in a.; c) charred heathland surface from the 1995 Frensham Fire, Surrey, U.K.; d) charcoal, mainly wood, from the 1995 Frensham Fire, Surrey, U.K.; e) charcoal from the 1995 Frensham Fire, Surrey, U.K. showing charred fern litter; f) heather dominated charcoal from the 2006 Thursley Fire, Surrey, U.K.; g) charcoal from the 1995 Frensham Fire, Surrey, U.K. showing wind concentrations of *Calluna* flowers; h) heather dominated charcoal from the 2006 Thursley Fire, Surrey, U.K. showing wind concentrated of *Calluna* flowers.

Figure 3. Scanning electron microscopy of modern charcoalified plants - Charcoal from the 1995 Frensham Fire, Surrey, U.K. (after Scott et al. 2000): a) wood of *Pinus*.; b) leaves of *Calluna*; c) detail of *Pinus* wood showing fusion of the middle lamella; d) *Calluna* flower; e) reflected light photo of charred *Pinus*; f) Charred moss.

Figure 4. Fossil charcoal assemblages: a) wood charcoal in fluvial Jurassic sandstone, Yorkshire, U.K.; b) macerated limestone with charcoal fragments and uncharred megaspores from the Mississippian of Scotland; c) small charcoal fragments from a Palaeocene silty-mudstone, Colorado, U.S.A.; d) detail of c showing charcoalified wood fragment; e) maceration of Upper Cretaceous clastic sediment yielding Charcoal from Japan; f) maceration from Upper Cretaceous muddy siltstone yielding charcoalified flowers, Sweden.

Figure 5. Scanning electron microscopy of fossil charcoalified plants: a) charcoalified conifer from the early Pennsylvanian, Illinois, U.S.A.; b) detail showing stomata with over-arching papillae; c) charcoalified pteridosperm leaf from the late Mississippian of Scotland; d) detail of c showing the leaf surface with stomata; e-g) charcoalified ovule from the Mississippian of Scotland; e) whole ovule showing ovule lobes and glandular hairs; f) showing spirally arranged glandular hairs; g) detail of glandular hairs.

Figure 6. Charring of *Sequoia* wood showing the homogenization of the cell wall: a) uncharred showing middle lamella; b) 350^{o}C showing presence of middle lamella; c) 350^{o}C showing the homogenization of the cell wall; d) 400^{o}C showing the homogenization of the cell wall (from McParland et al. in press).

Figure 7. a) reflectance of experimentally charred *Sequoia* wood charred for different temperatures and times (after Scott and Glasspool 2006b); b) reflectance of experimentally charred *Sequoia* at different temperatures for 24 hours. This data can give the minimum fire temperatures for wildfire charcoals.

Figure 8.Transport and deposition of charcoal: a, b) from a forest fire by overland flow from the Rodeo-Chediski Fire, Apache-Sitgreaves National Forest, Arizona, U.S.A., 2002 (Photo D. Neary); c-d) fossil sediments yielding charcoal; c) Mississippian near-shore marine sediments with abundant charcoal from the Mississippian of Donegal, Ireland; d) sandy siltstones with charcoalified conifer needles from the early Pennsylvanian, Illinois, U.S.A.; e) silty mudstones with abundant charred ferns, Lower Cretaceous of the Isle of Wight, U.K.

Figure 9. Waterlogging rates for different charcoalified plants and plant organs (after Scott 2000a): a) *Pinus* charred at different temperatures; b) Different organs of charred *Pinus*; c) different charred wood species; d) different size classes of wood charcoal.

Figure 10. The relationship between temperature of charcoal formation and time taken to sink (after Vaughn and Nichols 1995).

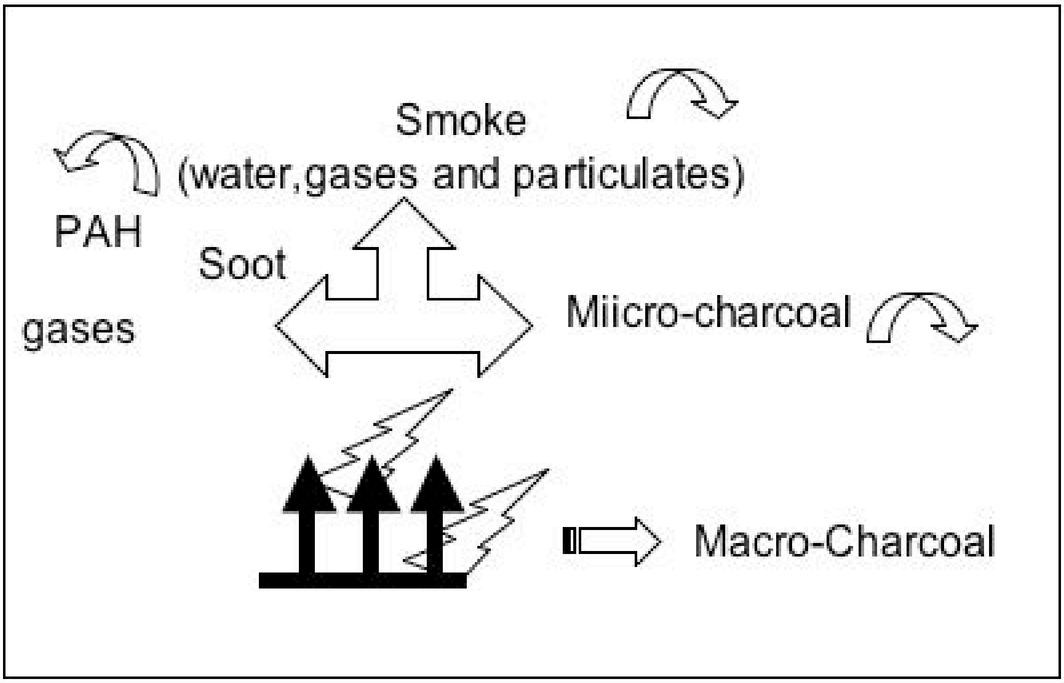
Figure 11. Experimental flume results incorporating charcoal into bedload sands. (after Nichols et al. 2000).

Figure 12. The occurrence of charcoal and interpreted fires systems in relation to modeled atmospheric oxygen for the Paleozoic (after Scott and Glasspool 2006a).

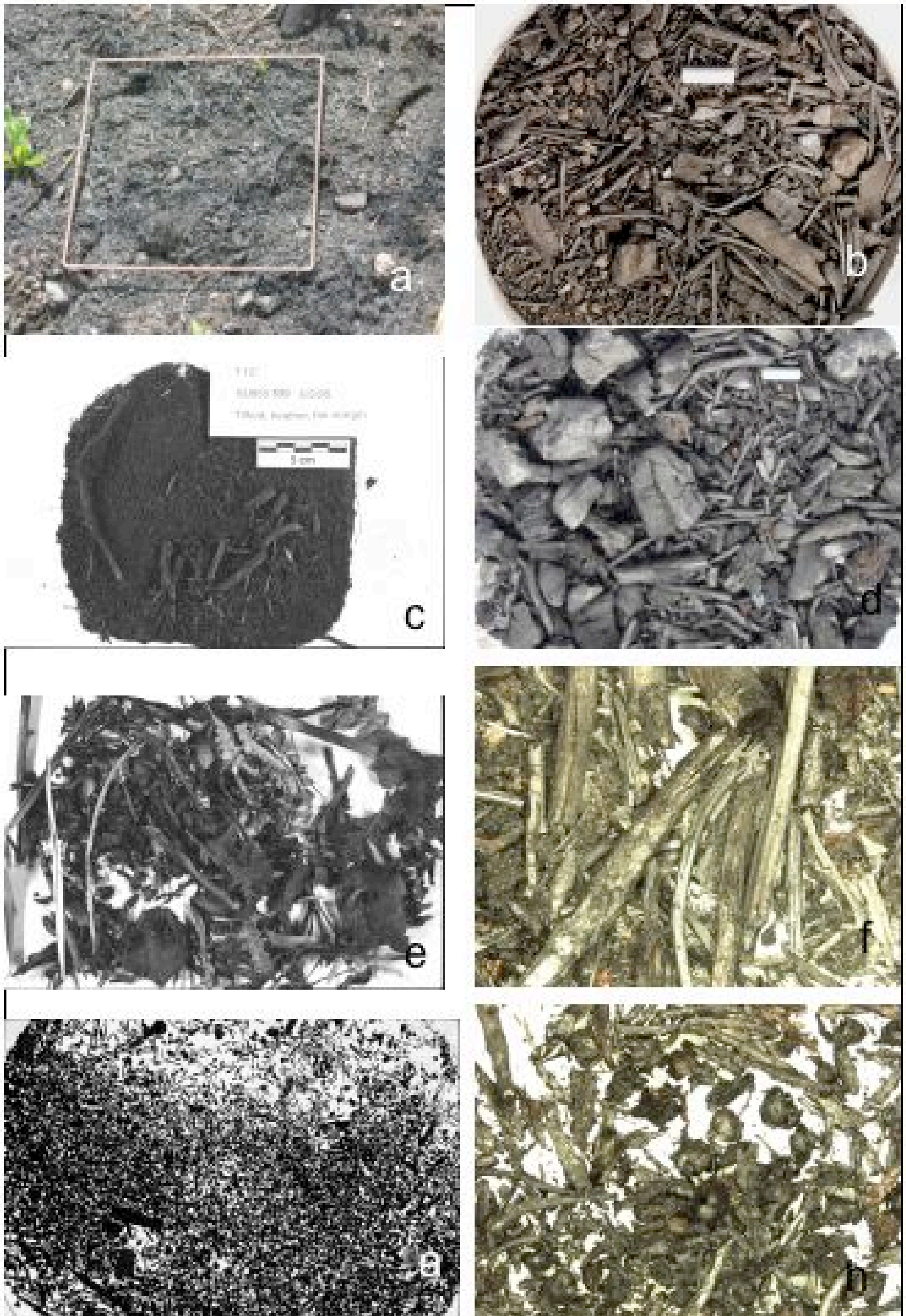
Figure 13. Systems analysis showing the feedbacks between fire and atmospheric oxygen.
Arrows originate with causes and end at effects. Plain arrows indicate direct responses, and arrows marked with bull's-eyes show inverse responses. Closed loops with an even number of bull's-eyed arrows or solely plain arrows are positive feedbacks, and those with an odd number of arrows with bull's eyes are negative feedbacks. Straight arrows lead to a positive response (eg. oxygen increases, fires increase) and arrows with bullseyes are negative responses (e.g. fires increase, vegetation decreases). A closed loop with an odd number of bullseyes leads to negative feedback and stability. An even number or no bullseyes leads to positive feedback and enhancement (but not always destabilization as can be shown mathematically). (after Berner et al. 2003).

Figure 14. Fire fundamentals triangles: a) fire fundamentals triangle (after Pyne etal. 1996); b) fire environment triangle (after Pyne et al. 1996); c) palaeofire triangle (after Scott 2000).

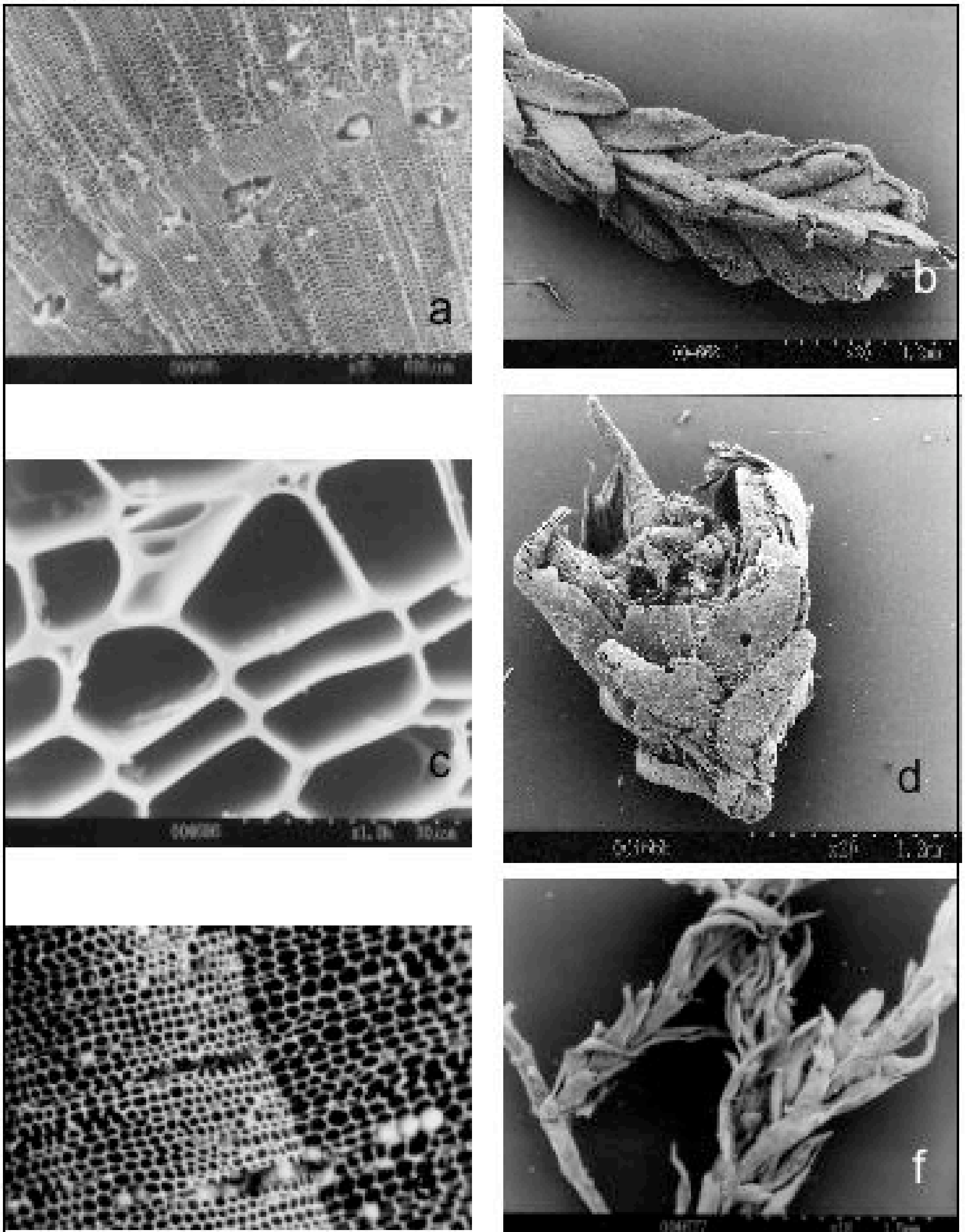
Scott Figure 1



Scott Figure 2

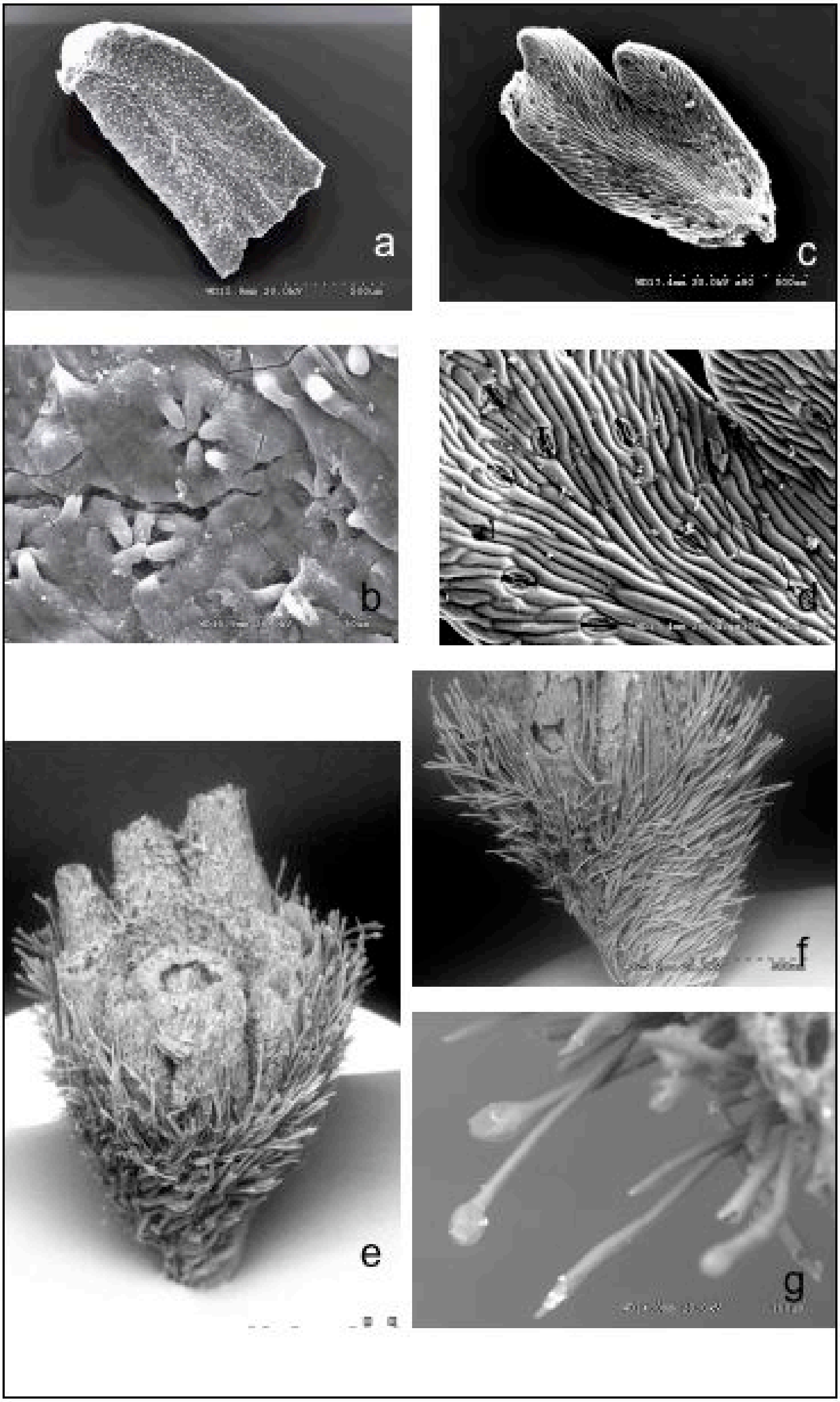


Scott Figure 3

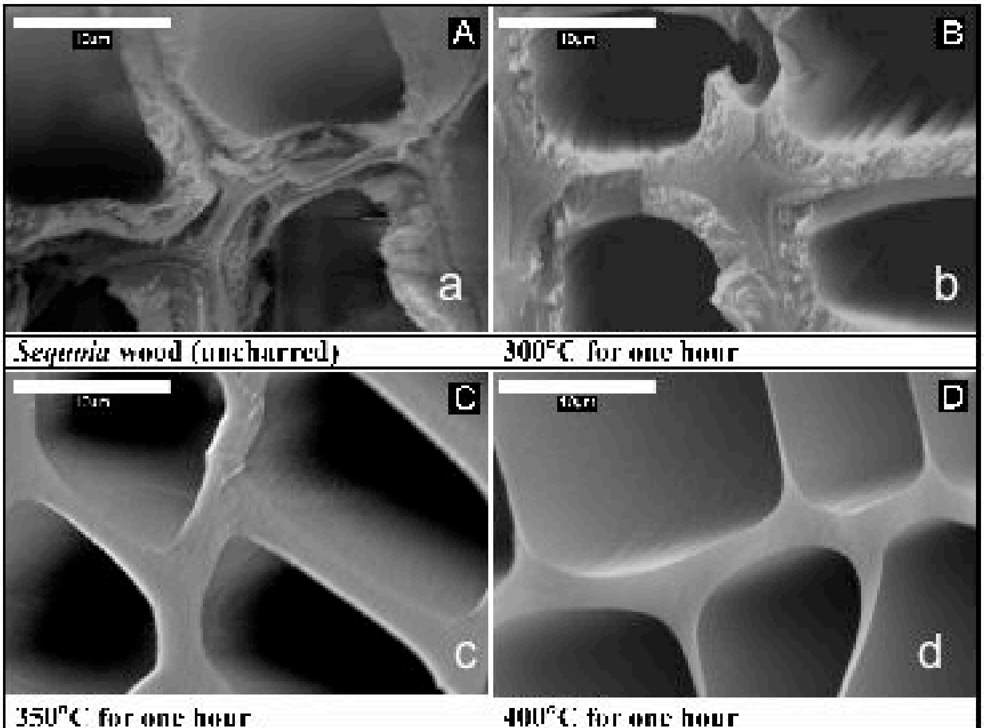


Scott Figure 4

Scott Figure 5



Scott Figure 6



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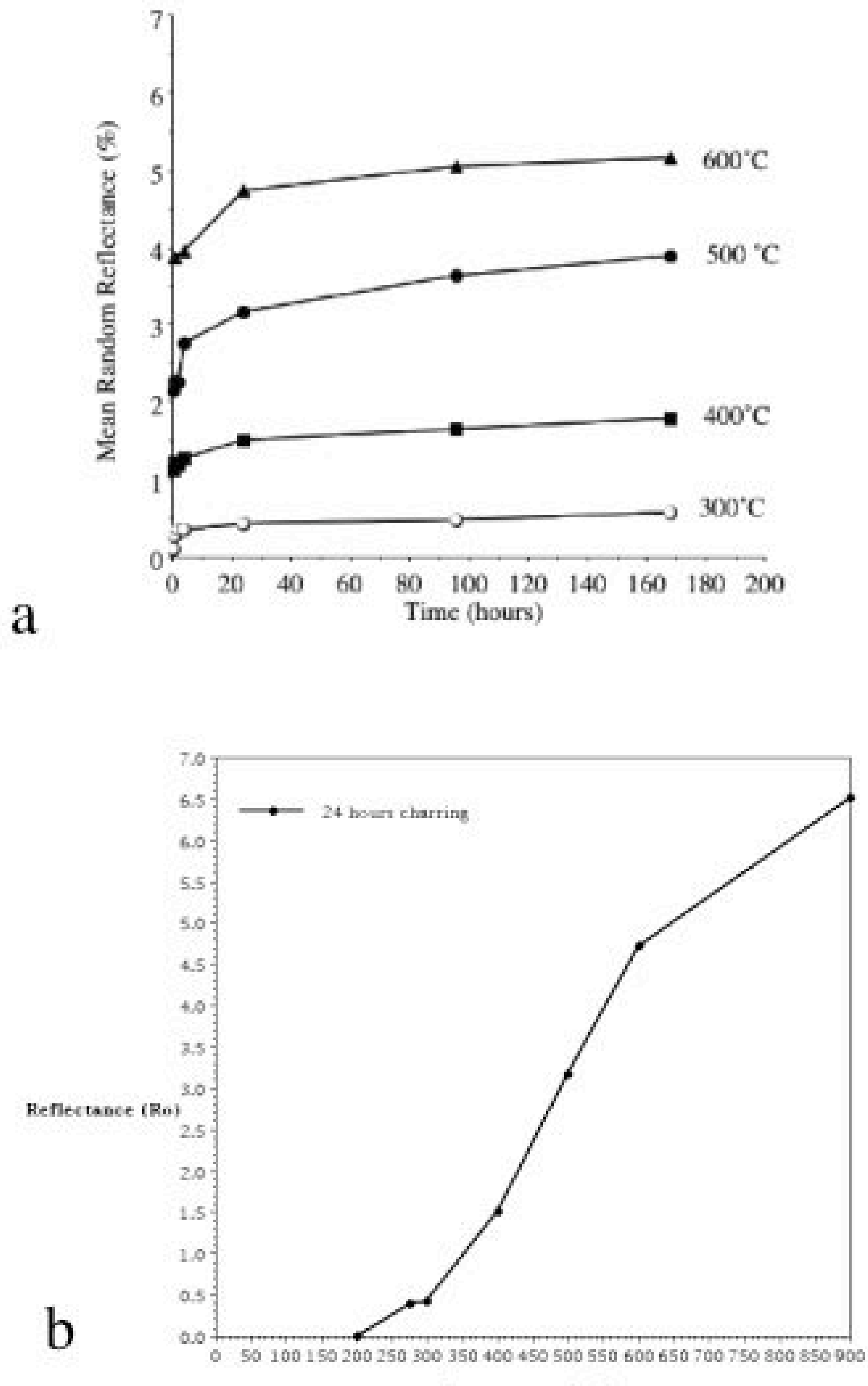

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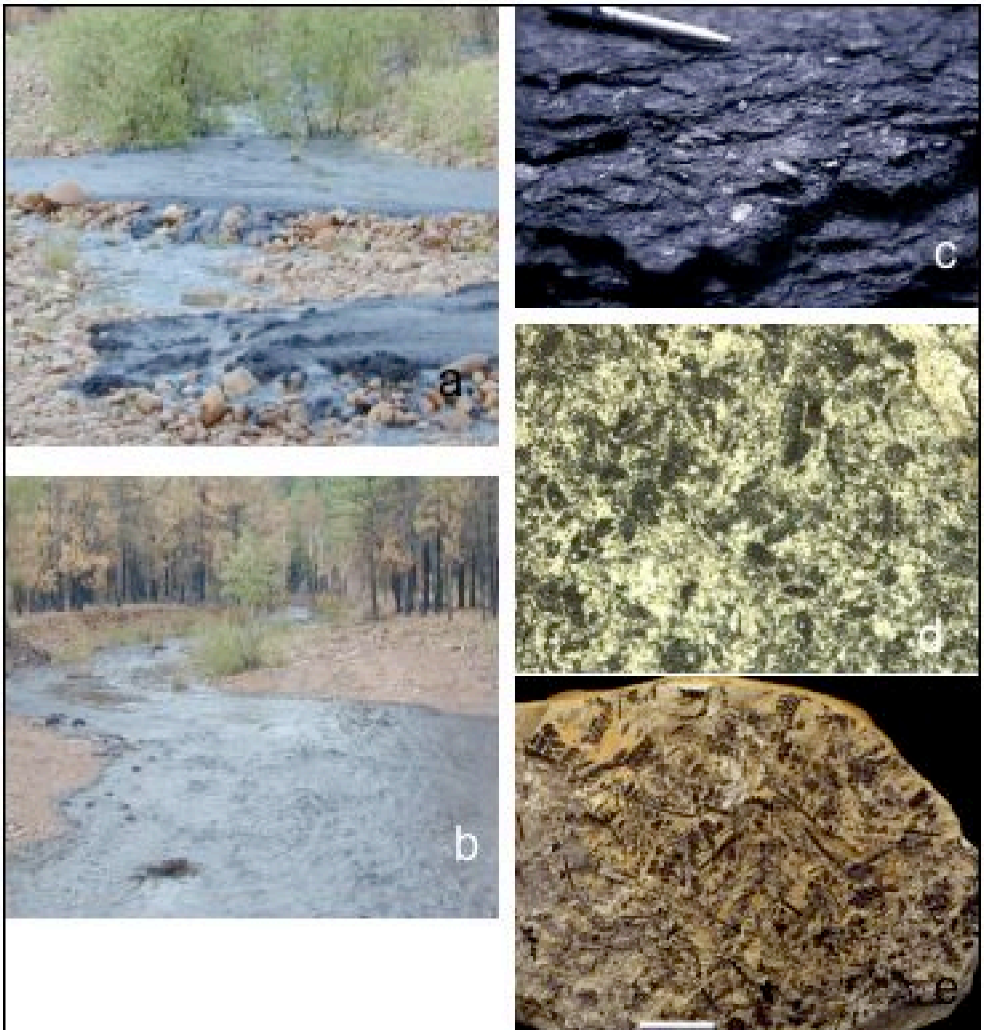
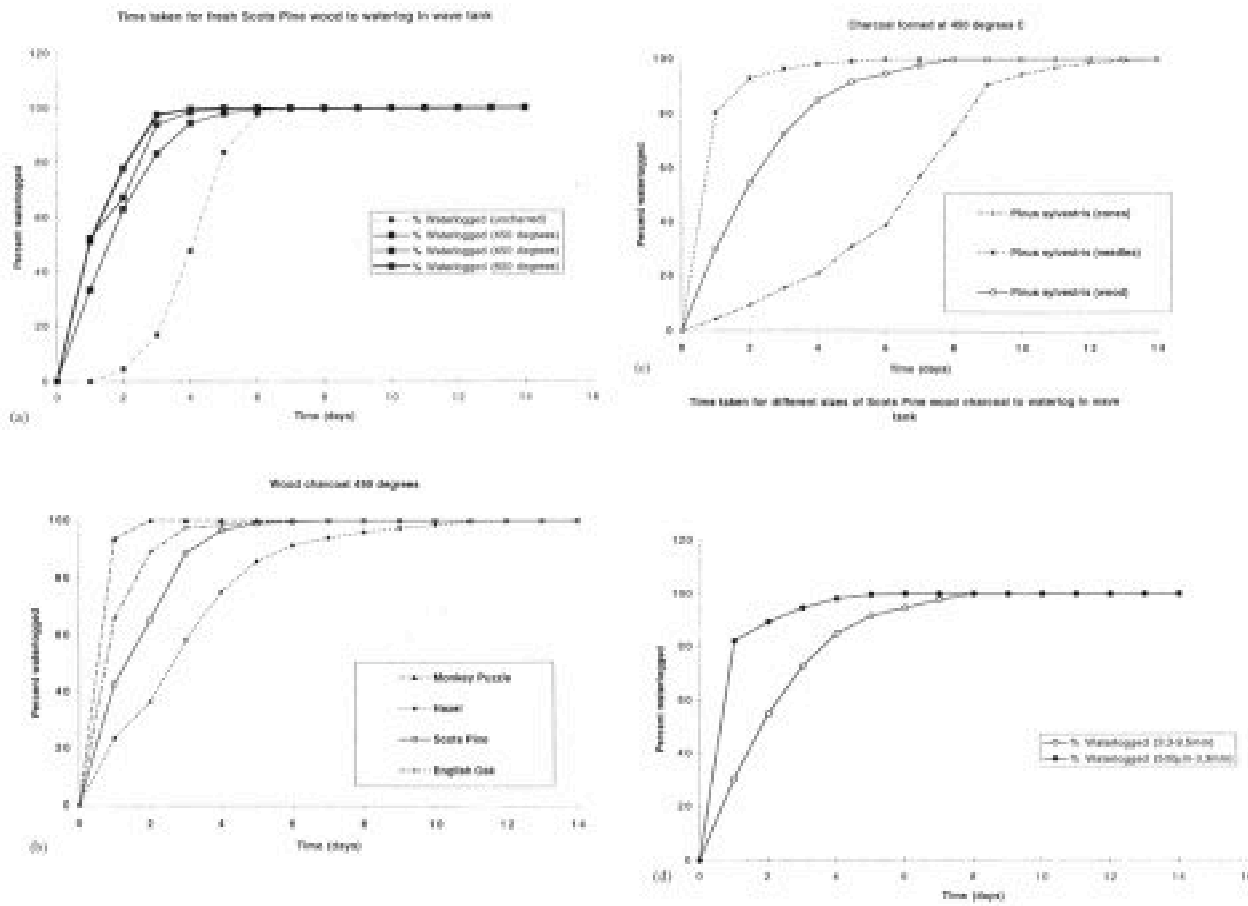
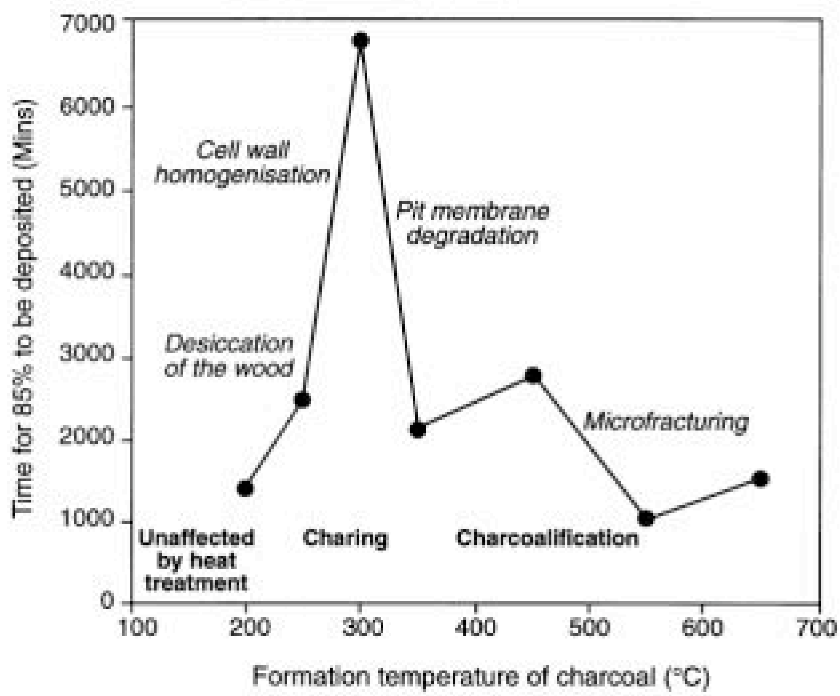


Scott Figure 9



Scott Figure 10



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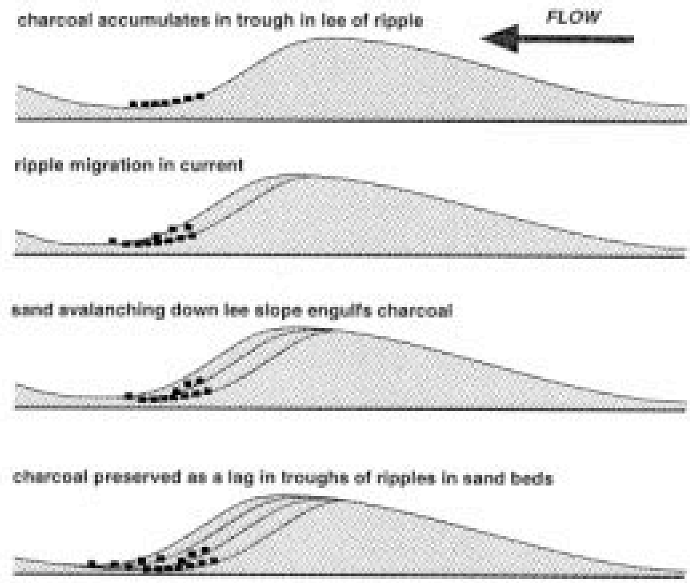

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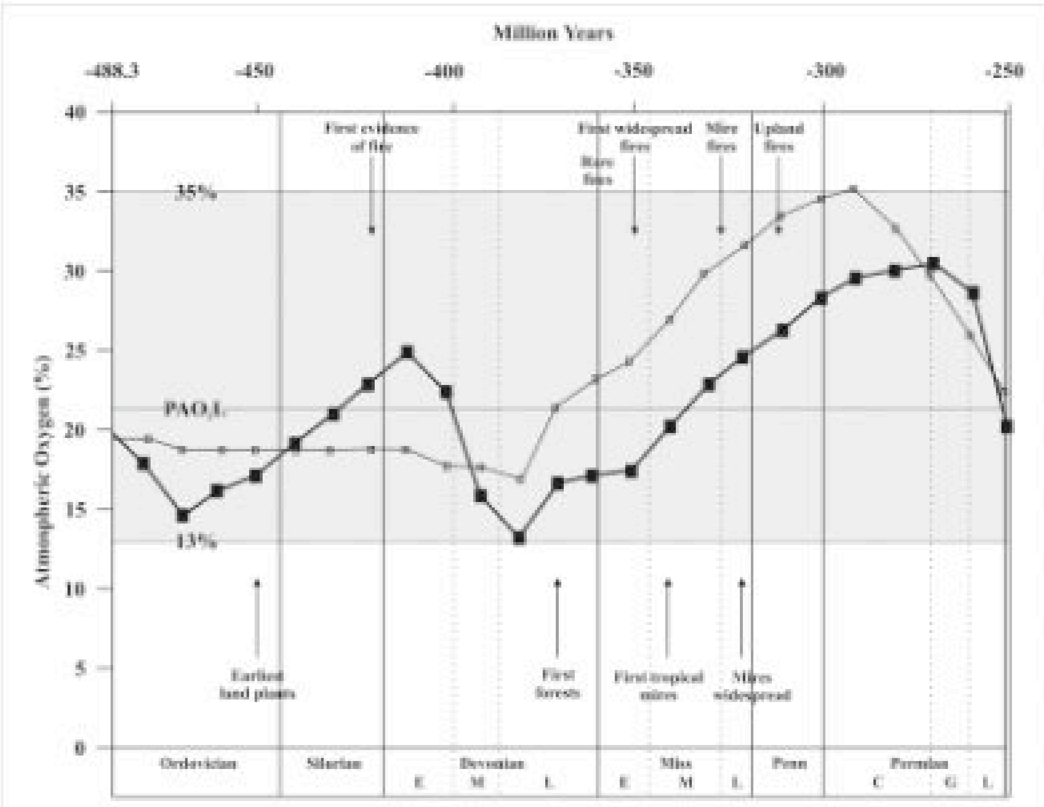

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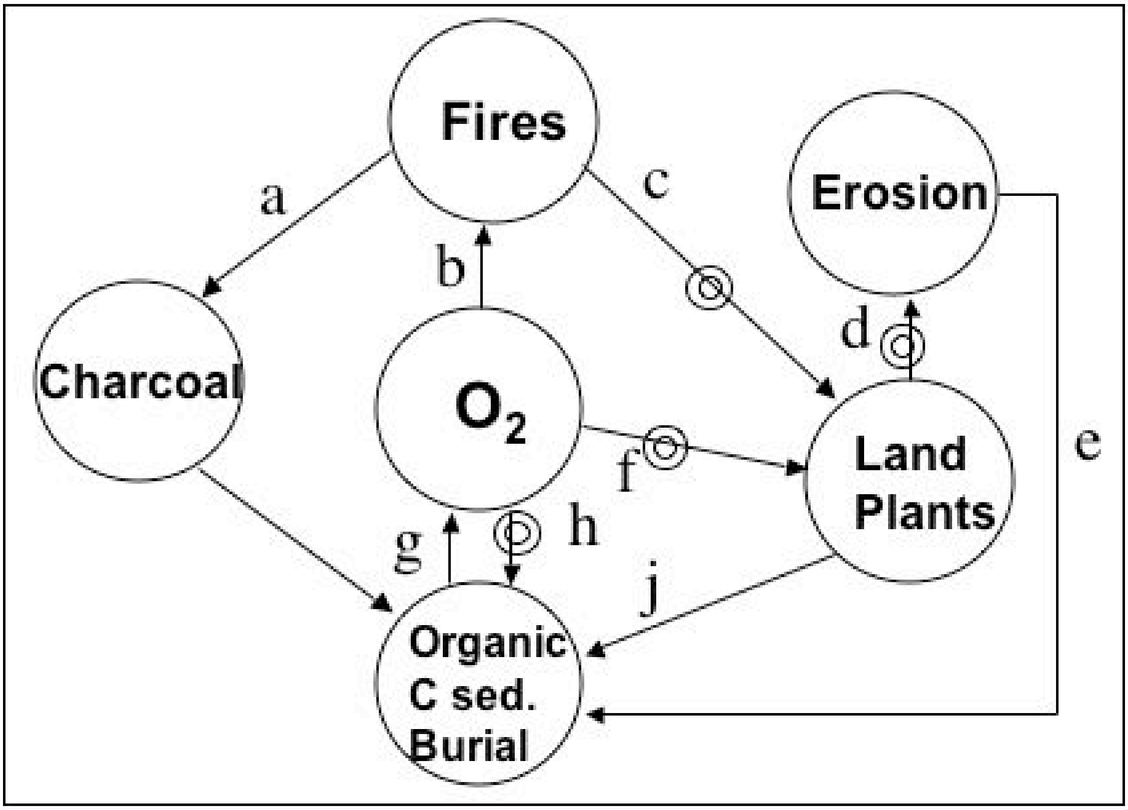

Scott Figure 14